N-70-34152

NASA TECHNICAL MEMORANDUM

NASA TM X-52847

NASA TM X-52847

STATIC TESTS OF 4-INCH-OUTSIDE-DIAMETER FRANGIBLE TUBE ENERGY ABSORBERS FOR NUCLEAR AIRCRAFT

by Klaus Gumto and Richard Puthoff
Lewis Research Center
Cleveland, Ohio

STATIC TESTS OF 4-INCH-OUTSIDE-DIAMETER FRANGIBLE TUBE ENERGY ABSORBERS FOR NUCLEAR AIRCRAFT

by Klaus Gumto and Richard Puthoff

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

Ten frangible tubes with outside diameters more than $3\frac{1}{2}$ inches (9 cm) were statically tested on a tensile machine. Five tubes failed to frange, while the results of the remaining five correlated with previous experiments. Problems were traced to load angle sensitivity, slow testing speed, and large tolerances of the as-received tubes.

E-5778

STATIC TESTS OF 4-INCH-OUTSIDE-DIAMETER FRANGIBLE TUBE ENERGY ABSORBERS FOR NUCLEAR AIRCRAFT

by Klaus Gumto and Richard Puthoff

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

SUMMARY

Application of the frangible tube energy absorber to a nuclear airplane reactor system is being considered. Its function is to absorb impact loads and to protect the fission product containment vessel which surrounds the reactor core.

Of all the energy absorbers available, the frangible tubes appear to be one of the most efficient. NASA Langley Research Center recently conducted tests on the frangible tubes. These tests revealed a potential for high specific energies. The tubes were made from both aluminum and high strength steels, with outside diameters ranging from 1/4 to 3 inches (0.635 to 7.62 cm). Tubes of this size, however, were not capable of absorbing the impact energy of a fission product containment vessel

A test program was conducted at Lewis Research Center to test materials, tube sizes and die configurations most applicable to the nuclear airplane. The tube sizes were larger than those previously tested. The franging process was observed and emphasis placed upon the tubes fragmenting performance when using as-received tube dimensions and normal tube alinement procedure. A total to ten tubes were tested in this program. The tests were conducted with a 120 000 lb (534 000 N) tensile machine.

The tubes tested had inside diameters of 3.14 inches (7.98 cm) and the tube wall thickness varied from 0.241 inch (0.661 cm) to 0.438 inch (1.11 cm). The tube wall thickness to die forming radius ratios (t/r) ranged from 0.271 to 0.492. Some difficulty was experienced in getting the tubes to frange. Longitudinal splitting resulted in erratic tube loading.

Following the tests, the specific energy was determined for each tube which franged properly. Specific energies varied from 3292 ft-lb/lb (9880 J/kg) for an aluminum tube with a t/r of 0.174 to

9155 ft-lb/lb (27 450 J/kg) for a steel tube of 0.434 t/r. The test results correlated with Langley data.

The following conclusions were reached from the results of the tubes that were tested.

1. The franging process was very sensitive to the load angle.

2. Tubes and dies may require close machining tolerances for assured operation.

3. Slow speed testing resulted in erratic tube loading and poor franging performance.

The close machining tolerances required for fragmentation is expected to increase system fabrication costs significantly. Also, operational reliability of an energy absorption system employing frangible tubes may be low because of its load angle sensitivity.

SYMBOLS

D_i	inside diameter of tube, in. (cm)
D_o	outside diameter of tube, in. (cm)
k	prefix - Kilo - 10^3
M	prefix - Mega - 10^6
r	die forming radius, in. (cm)
Spe	specific energy, ft-lb/lb (J/kg)
t	wall thickness of tube, in. (cm)
ρ	density, lb/cu in. (grams/cm^3)
σ_f	franging stress, psi (MN/m^2)
σ_θ	hoop stress, psi (MN/m^2)
σ_z	longitudinal tube stress, psi (MN/m^2)

INTRODUCTION

Application of energy absorbers to a nuclear airplane reactor system are being considered because fission products must be contained in the event of an aircraft accident. The energy absorber surrounds the fission product containment vessel absorbing the impact loads during an aircraft crash.

Frangible tubes possess the high specific energy required for application to the nuclear airplane. Their high energy absorption capability and simple design could result in a dependable system at reasonable cost, if standard tubes could be used and if tube and die alinement was not critical.

The frangible tube, recently tested by NASA Langley Research Center, is an energy absorber that appears to have one of the highest energy absorption capabilities per pound of absorber plus structure. The frangible tube is a thick walled tube of metal which is placed over a flared die. A compression load forces the tube onto the die where tube fragmentation occurs. This process forces the tube material into the plastic regime, thus extracting the maximum amount of strain energy.

The tubes tested by Langley consisted of aluminum and high-strength steels. The maximum specific energies were 30 000 ft-lb/lb (90 000 J/kg) for 2024 T3 aluminum and 38 000 ft-lb/lb (114 000 J/kg) for AISI 4130 steel. Tube sizes tested varied from 1/4 inch (0.635 cm) to over 3 inches (7.62 cm) in diameter.

A test program was conducted at Lewis Research Center to test candidate nuclear airplane frangible tubes. Its purpose was to test materials, tube sizes and die configurations most applicable to the nuclear airplane. The tube diameters and strength-to-weight ratio were greater than those tested to date. The franging process was observed and emphasis placed upon the tubes fragmenting performance when using as-received tube dimensions and minimum tube alining procedure. The results of these tests were expected to be useful in the design of a reliable and inexpensive impact absorber system using "off-the-shelf" type components. This experimental program was conducted concurrently with a conceptual design study of a nuclear airplane energy absorber using frangible tubes (ref. 1).

DESCRIPTION OF EXPERIMENTAL FACILITY

The experimental facility consisted of a 120 000 lb (534 000 N) tensile machine operated to apply a load between the cross bar and the movable table (see fig. 1). A load rate of 2 inches (5.08 cm) per minute was used. The tube and die were located between these. A fixture attached to the cross bar located the tube, while another adjustable fixture attached to two uprights permitted centering of the die. A strain gage load cell was placed between the table and die to measure the applied force. The signal from the load cell was fed into a strain gage bridge signal conditioner and power supply unit and from there to the Y-axis of an X-Y plotter. A linear potentiometer measured the upward displacement of the table with a range of 7.5 inches (19 cm). This displacement was recorded on the X-axis of the recorder. A clear plastic shield surrounded the tensile machine for containment of any flying fragments.

DESCRIPTION OF TEST SPECIMENS

The frangible tube assembly consists of a tube and die. The die was common to all tubes tested. The dies were machined from AISI 4130 steel, heat treated to a Rockwell - C hardness of 42 - 44. The die was designed using the method of reference 2 and had a forming radius of 0.89 inch (2.26 cm) and a 5° taper on the shank (see fig. 2).

Both 2024 T3 aluminum and AISI 4340 steel tubes (heat treated to a hardness of RC 38) were purchased for testing. The tubes had a 3.124-inch (7.935 cm) inside diameter and a 7/16-inch (1.11-cm) wall thickness in the as-received condition. All tubes were cut to a 12-inch (30.5-cm) length and the outside diameter machined to the desired wall thickness. These were 0.312 inch (0.793 cm), 0.356 inch (0.905 cm), 0.400 inch (1.016 cm), and 0.438 inch (1.11 cm) for the aluminum tubes, and 0.255 inch (0.648 cm) and 0.290 inch (0.737 cm) for the steel tubes. The die end of all tubes received a 15° taper on the outside, starting at the inside diameter.

EXPERIMENTAL PROCEDURE

Ten tubes were tested on the tensile machine. These are listed in table I. Testing of these tubes was conducted in the order that they appear in the table. The following is a description of the testing of each tube.

Prior to testing all instruments were calibrated. A load scale was established for the load cell by increasing the force in 5000 lb (22 200 N) increments up to 70 000 lb (311 000 N), and back to 0 in 5000 lb (22 200 N) steps. The same procedure was followed after the test to insure that the calibration had not changed. Next, the equivalent load values were determined for six settings of the calibration resistor built into the signal conditioner. This permitted the deflection of the recorder along the Y-axis (applied force) to be calibrated prior to each test.

Similarly, the linear potentiometer which measured the table displacement was calibrated over its 7.5 in. (19.0 cm) range initially, and was rechecked for a displacement of 2 in. (5 cm) and 7.5 in. (19 cm) before each run.

The alinement of the tube with the die axis was checked before each test using a square and level. (It was felt that a more accurate check should not be required in a "production type" energy absorbing system.) Next, the load was applied by manually operating the controls of the tensile machine. A successful test ended when the upper locating fixture made contact with the die shank after franging 7.5 in. (19 cm) of the tube.

Following the tests, the specific energy was determined for each tube which franged properly. The area under the load-displacement curve was measured with a planimeter. The resulting value was divided by the weight of the first 7.5 in. (19.0 cm) of the tube, i.e., the weight involved in the franging process. This gave the specific energy. For the tapered tubes, an average t/r was calculated using the average wall thickness over the franged part. Table II shows the results. Similarly, the franging stress was calculated by dividing the area under the load - displacement curve by the stroke to get the average load. The average load was divided by the tube cross-sectional area (average area for the tapered tubes). This gave the franging stress.

RESULTS

Tube Fragmentation

According to McGehee's results (ref. 3) tube 1 should require about 63 700 lb (284 000 N) of force to frange. After inserting the tube in the rig, the load was gradually applied. The tube began to expand as it was forced over the die shank. At 38 000 lb (169 000 N) load, longitudinal cracks appeared around the circumference, spaced about 2.5 inch (6.35 cm) apart. These cracks propagated up the tube. Along with the cracking, the tapered part of the tube began bending around the die radius, breaking off the tip of the taper. A further increase in the load up to 69 300 lb (308 000 N) produced no franging. At this point it was decided to discontinue the test and attempt to frange a thinner walled tube.

Tube 2 behaved like tube 1, even though the predicted load was only 25 250 lb (112 000 N). A maximum load of 108 500 lb (482 000 N) produced no franging.

It was discovered that both tubes had formed a "tripod" which resisted franging. Analysis of the specimens showed that the inside diameter of the tubes was less than that allowed by specified tolerances. This resulted in the tube engaging the die shank at the taper rather than the die radius. The distance between the longitudinal cracks was large, resulting in a small number of wide tube segments (ribbons), which resisted bending around the die radius. Instead, the ribbons bent away from the shank and contacted the die in the die forming radius perpendicular to the surface, thus forming the "tripod" arrangement (fig. 3). This prevented any further displacement as the capacity of the tensile machine was insufficient to bend the wide ribbons or cause column failure in the tube.

To prevent this from occurring with future tubes, the inside diameter of the remaining tubes (except tube 3) was enlarged by 0.009 in. (0.023 cm) to a diameter of 3.142 in. (7.98 cm). While these tubes were being machined, tube 3 received a shallow taper of 1.5° on the outside, producing a wall thickness of 0.065 in. (0.165 cm) at the die end and increasing to the full wall thickness of 0.312 in. (0.793 cm) at 9.5 in. (24.1 cm).

Upon testing, the tube went through an expansion and longitudinal splitting stage, followed by a curling of the split segments (McGehee's rolling, Ref. 2). Franging began when tube thickness became greater than 0.232 in. (0.59 cm), corresponding to a t/r of 0.261 and continued for the remainder of the stroke.

The shallow taper permitted a gradual buildup to full load. This appears beneficial to the franging process. Tube 4, the first tube with the proper inside diameter, also received a taper. This 2° taper began with a wall thickness of 0.050 in. (0.127 cm) at one end and increased to 0.345 in. (0.9 cm) at 9 in. (22.8 cm) from that end. This tube behaved like tube 3, proceeding through the same stages. Franging began at a t/r of 0.266 (wall thickness of 0.236 in. (0.60 cm)) and continued until the end of the stroke at a t/r of 0.346, which is a wall thickness of 0.308 in. (0.783 cm).

Tube 5 not only had a thicker wall than tubes 3 or 4, but also had a taper of 4°. Franging began at a wall thickness of 0.217 in. (0.551 cm) equivalent to a t/r of 0.244, and continued to the end of the stroke. For the last 2.75 in. (6.98 cm) of the stroke, the tube franged at its full thickness of 0.386 in. (0.98 cm), or t/r of 0.434.

Tube 6 was the first steel tube to be tested. It had a 2.6° taper over the first 4.5 in. (11.4 cm) of the tube, followed by the full wall thickness for the remainder of the length. The tube franged smoothly after going through a rolling stage while on the tapered portion of the tube. A peak franging load of 108 000 lb (480 000 N) was required to initiate franging, followed by an average of 66 000 lb (293 000 N) for the remainder of the stroke.

Tube 7 was the first tube to frange completely with the standard 15° taper. Although the predicted average franging load was 22 500 lb (100 000 N), the load required to begin franging was 93 000 lb (413 000 N), which was 3.5 times greater than the actual average load of 28 000 lb (124 000 N).

Tube 8 was similar to tube 7 except for a thicker wall, resulting in a larger t/r of 0.382. From McGehee's results, the predicted load to sustain franging was 31 250 lb (139 000 N). Figures 4 to 8 show the sequence of this tube during testing. Although, the load was increased to the capacity of the machine, i.e., 120 000 lb (534 000 N), the tube did not frange. Tube 10, with a nearly equal t/r of 0.387 behaved likewise. Apparently the machine was not capable of starting the franging process with a taper as great as 15°.

Tube 9, the second steel tube, behaved differently. At a load of 108 000 lb (480 000 N), a single crack developed, traveling 10 in. (25 cm) up the tube. Later, it was discovered that the upper locating fixture had shifted about 0.125 in. (0.318 cm) off axis, producing an angular deviation of less than 1°. Apparently, this small angle was sufficient to make franging impossible.

At this time, it was decided to discontinue tests, since the machine was not capable of franging the tubes in the range of wall thicknesses desired. It was also apparent that the franging process was very sensitive to the load angle, much more so than was considered desirable. It was also felt that the tubes and dies may require close machining tolerances for assured operation. This negated the idea of a low cost, "off-the-shelf" type impact absorbing system requiring a minimum of alining.

Tube Specific Energy

Table II lists the specific energies and franging stresses determined from the test results. Note that the specific energies and franging stresses for tubes 3 and 4 are average values over the taper, while the results for tubes 5 and 6 were calculated from the data over the untapered part of the tube. The results for tube 7 include the 15° taper.

Figure 9 shows the test results compared to McGehee's aluminum tube data. The solid curve is for tubes with D/r of 3.03, 3.44 and 4.20, and t/r from 0.295 to 0.475 (ref. 2). This figure shows that the results of these tests correlate well with McGehee's results. The AISI 4340 steel tube also compares well McGehee's AISI 4130 steel data, which is expected to be similar to AISI 4340 data. His curve predicts a franging stress of 22 ksi (151.5 MN/m^2) at t/r of 0.271, while the experimental franging stress was 25.8 ksi (178. MN/m^2).

FACTORS AFFECTING TUBE PERFORMANCE

Some observations were made during the test program which affect the desirability of performing static tests on frangible tubes. First, slow speed fragmentation of a tube will result in lower fragmenting stresses. This was noted by McGehee in reference 2 in which a fragmenting stress obtained at 12 000 in. (30 500 cm) per minute was about 60% higher than those obtained at one inch per minute. Since the specific energy of a frangible tube is expressed by

$$Spe = \sigma_f/\rho$$

the recorded specific energy for static tests will be lower by the same amount (60%). Therefore, static tests will yield conservative values and will not reflect the true potential of the tube.

Second, the fragmentation of a tube at high fragmenting stress levels results in uncontrolled axial tearing of the tube, and subsequent erratic fragmentation. This can best be explained as follows. The fragmenting stress of the tube is also the longitudinal tube stress σ_z. For a thin wall tube only two principal stresses occur σ_z and σ_θ. As the tube is forced upon the die radius σ_θ increases while σ_z remains fairly constant in the area of the taper. Soon a localized failure occurs in the tube and axial tearing of the tube commences.

As the tear propagates out of the high σ_θ region (or the die radius and taper region) tube failure should stop. This is particularly true when low σ_z (or σ_f) values occur. But if the tube is required to perform at its upper limit of σ_z value, the tear will continue well beyond the high σ_θ region because as the tear propagates axially, the tear point is fairly sharp, resulting in a stress riser. The axial stress (σ_z) at failure is lowered due to the stress riser. Under static test conditions a "tripod" develops (see figs. 7 and 8) and a column type loading occurs which is no longer a fragmenting process. Thus high loads are needed to begin franging.

Under dynamic conditions the same phenomena would occur. However, fragmentation will occur more rapidly, reducing the effect of the axial tear propagation. As a result the fragmentation is less erratic and a "tripod" type loading is less likely to occur.

CONCLUSION

Ten tubes were tested. Their wall thicknesses varied from 0.241 in. (0.661 cm) to 0.438 in. (1.11 cm). Their specific energies varied from 3292 ft-lb/lb (9880 J/kg) for an aluminum tube with a t/r of 0.174 to 9155 ft-lb/lb (27 450 J/kg) for a steel tube of 0.434 t/r. These low franging stresses and specific energies are a result of using small values of t/r which are less efficient. The test results correlated with NASA Langley data.

The following conclusions were reached from the results of the tubes that were tested.

1. The franging process was very sensitive to the load angle.

2. Tubes and dies may require close machining tolerances for assured operation.

3. Slow speed testing resulted in erratic loading and poor franging performance.

The close machining tolerance required for fragmentation is expected to increase system fabrication costs significantly. Also, operational reliability of an energy absorption system employing frangible tubes may be low because of its load angle sensitivity.

REFERENCES

1. Puthoff, Richard L.; and Gumto, Klaus H.: Parametric Study of a Frangible-Tube Energy-Absorption System for Protection of a Nuclear Aircraft Reactor. NASA TN D-5730, 1970.

2. McGehee, John R.: Experimental Investigation of Parameters and Materials For Fragmenting-Tube Energy-Absorption Process. NASA TN D-3268, 1966.

3. McGehee, John R.: A Preliminary Experimental Investigation of an Energy-Absorption Process Employing Frangible Metal Tubing. NASA TN D-1477, 1962.

TABLE I.- TUBE SPECIFICATIONS

Tube Number	Material	Inside Diameter, D_i		Tube wall thickness, t		Inside diameter to die forming radius ratio, D_i/r	Tube wall thickness to die forming radius ratio, t/r	Taper, degrees
		in.	cm	in.	cm			
1	Aluminum	3.124	7.935	0.438	1.110	3.52	0.492	15.0
2				.312	.793		.350	
3				.155[a]	.394[a]		.174[a]	1.5
4		3.142	7.981	.166[a]	.421[a]	3.54	.187[a]	2.0
5				.386	.980		.434	4.0
6	Steel			.241	.611		.271	2.6
7	Aluminum			.297	.755		.322	15.0
8				.340	.863		.382	
9	Steel			.233	.952		.262	
10	Aluminum			.344	.873		.387	

[a] averaged over the taper.

TABLE II.- TEST RESULTS

Tube number	Tube wall thickness to die forming radius ratio t/r	Specific energy		Franging stress		Average load		Weight of franged part	
		ft-lb/lb	J/kg $\times 10^3$	ksi	MN/m^2	lbs $\times 10^3$	N $\times 10^3$	lbs	kg
1	0.492	-	-	-	-	-	-	-	-
2	.350	-	-	-	-	-	-	-	-
3	.174[a]	3 292	9.88	3.95	27.2	6.3	28.0	1.28	0.58
4	.187[a]	4 331	12.95	5.20	35.9	9.2	40.9	1.31	.60
5	.434	9 155[b]	27.45[b]	11.00[b]	76.0[b]	47.0[b]	209.[b]	1.18[b]	.53[b]
6	.271	7 145[b]	21.40[b]	25.80[b]	178.0[b]	66.0[b]	293.[b]	2.27[b]	1.03[b]
7	.332	7 340	22.00	8.70	60.0	28.0	124.	2.26	1.02
8	.382	-	-	-	-	-	-	-	-
9	.262	-	-	-	-	-	-	-	-
10	.387	-	-	-	-	-	-	-	-

[a] averaged over the taper.

[b] untapered section only.

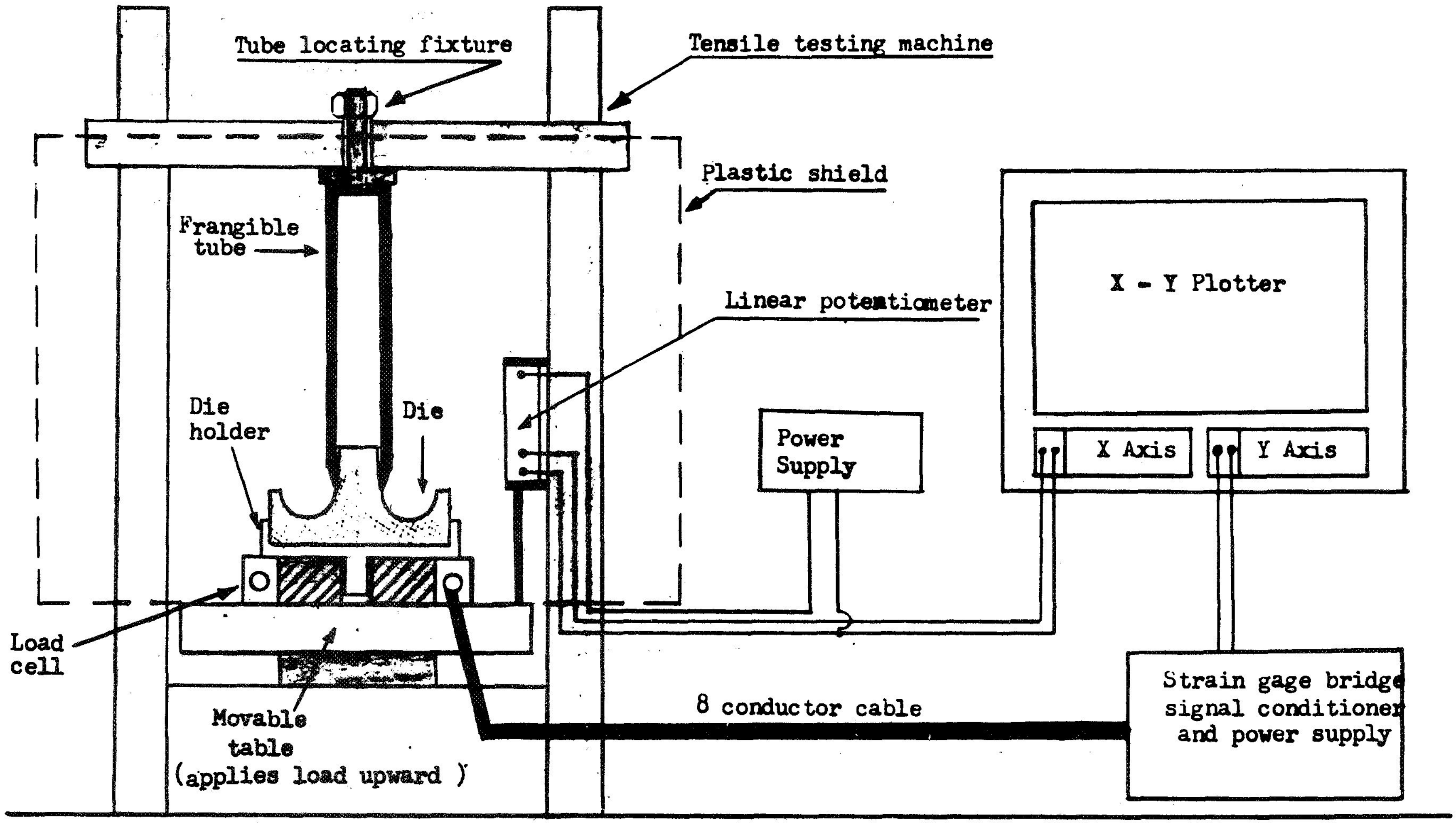


Figure 1 . Experimental facility (Schematic)

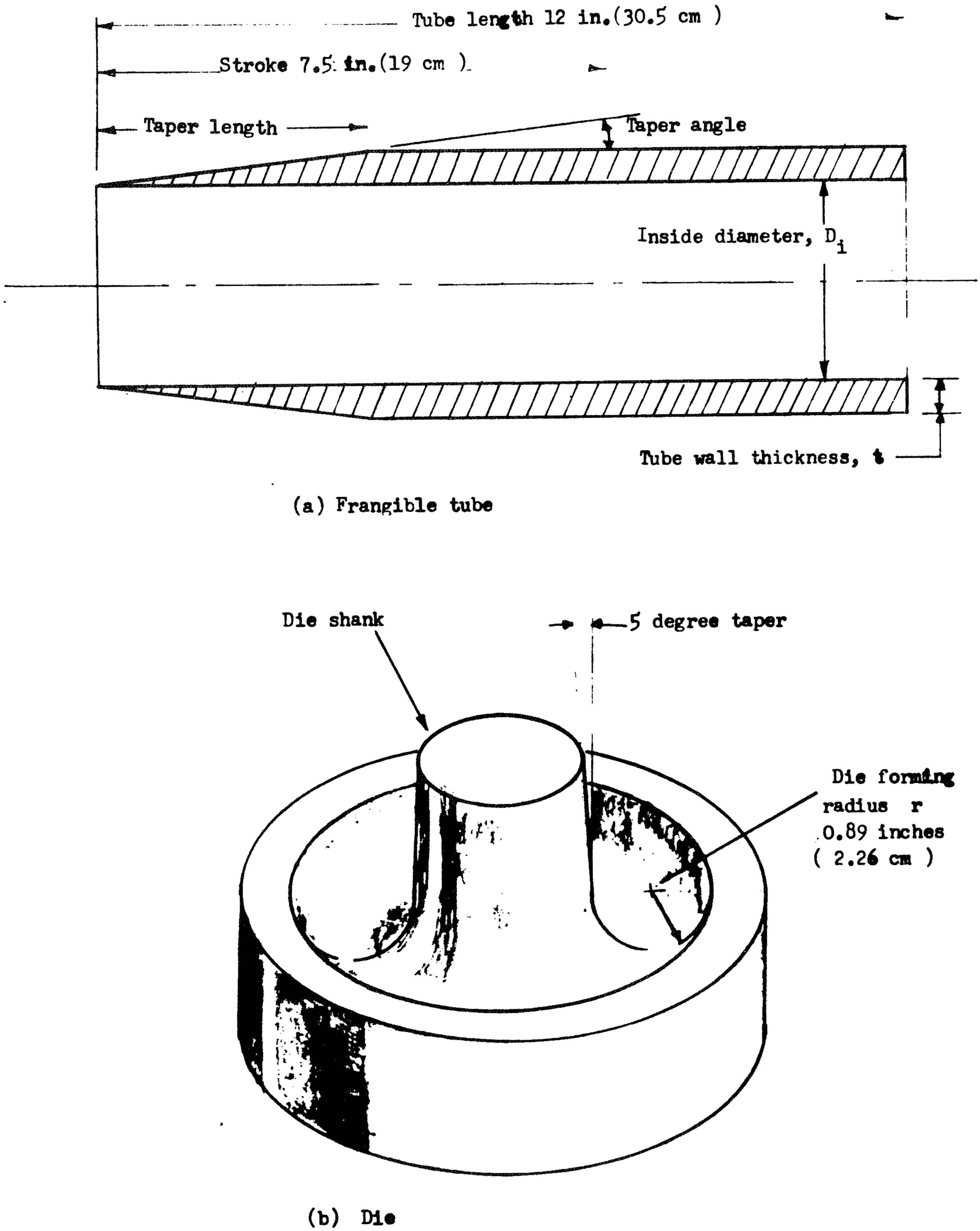


Figure 2. Frangible tube and die.

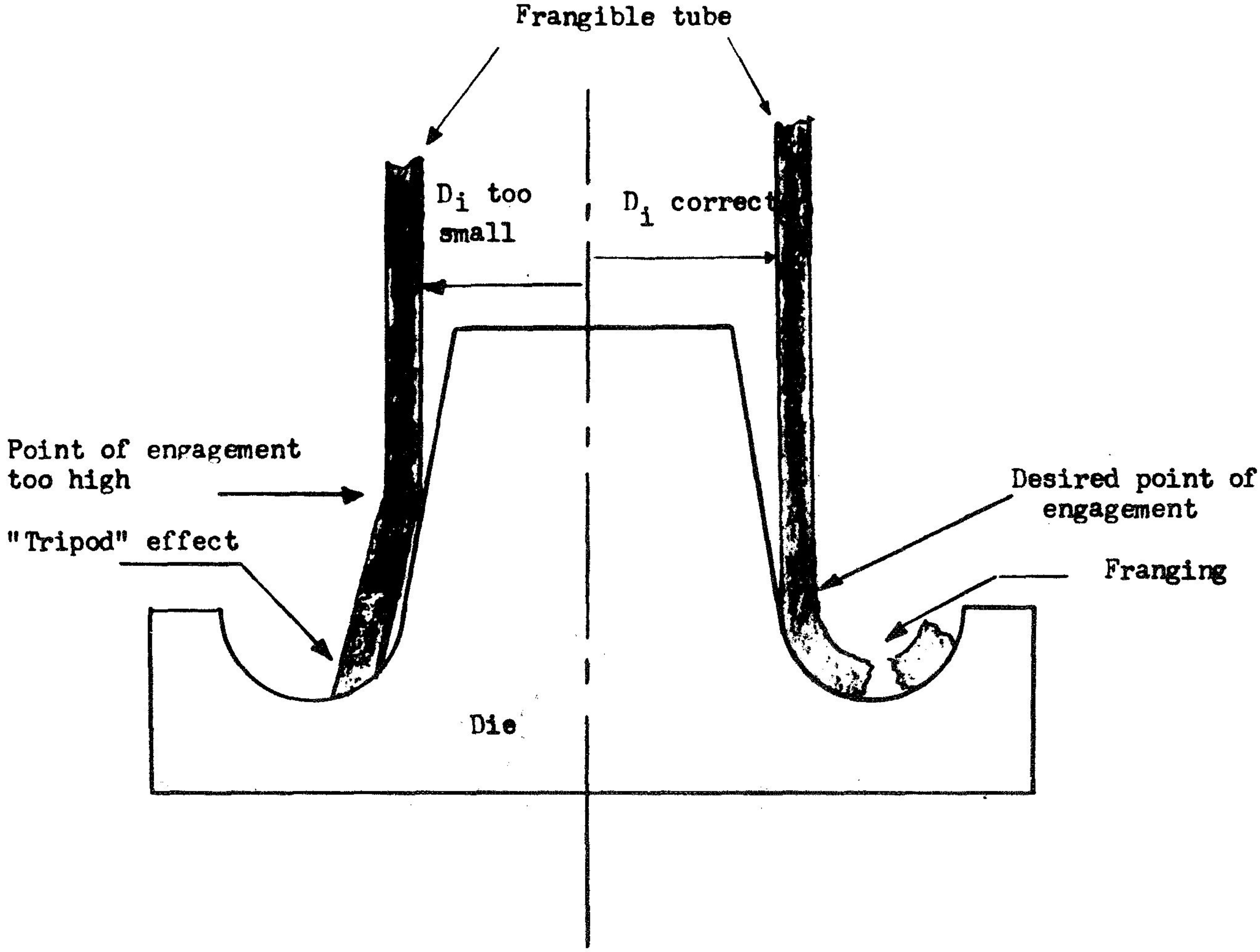


Figure 3. Correct and improper engagement of a frangible tube on the die.

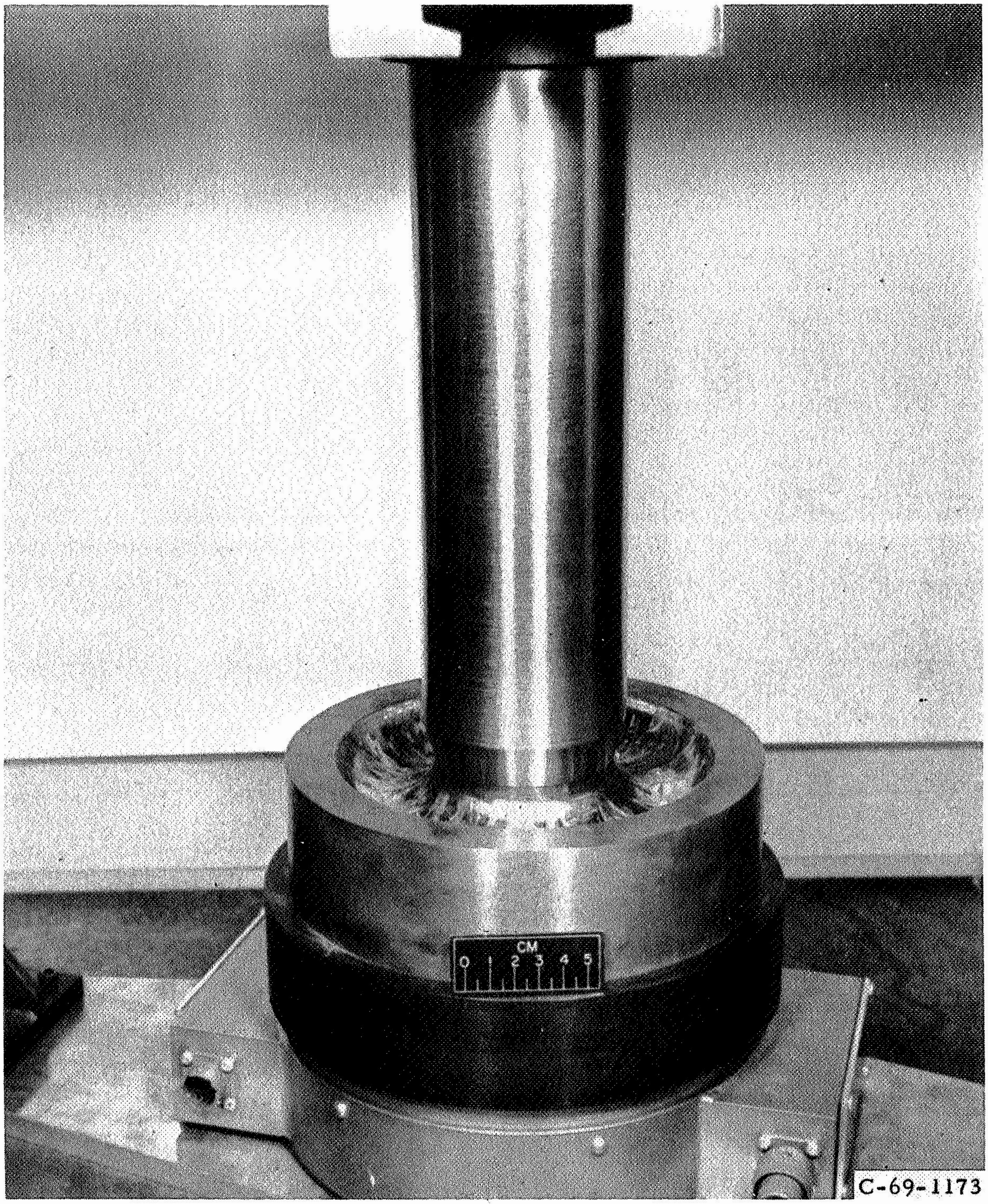


Figure 4. - Frangible tube and die before franging.

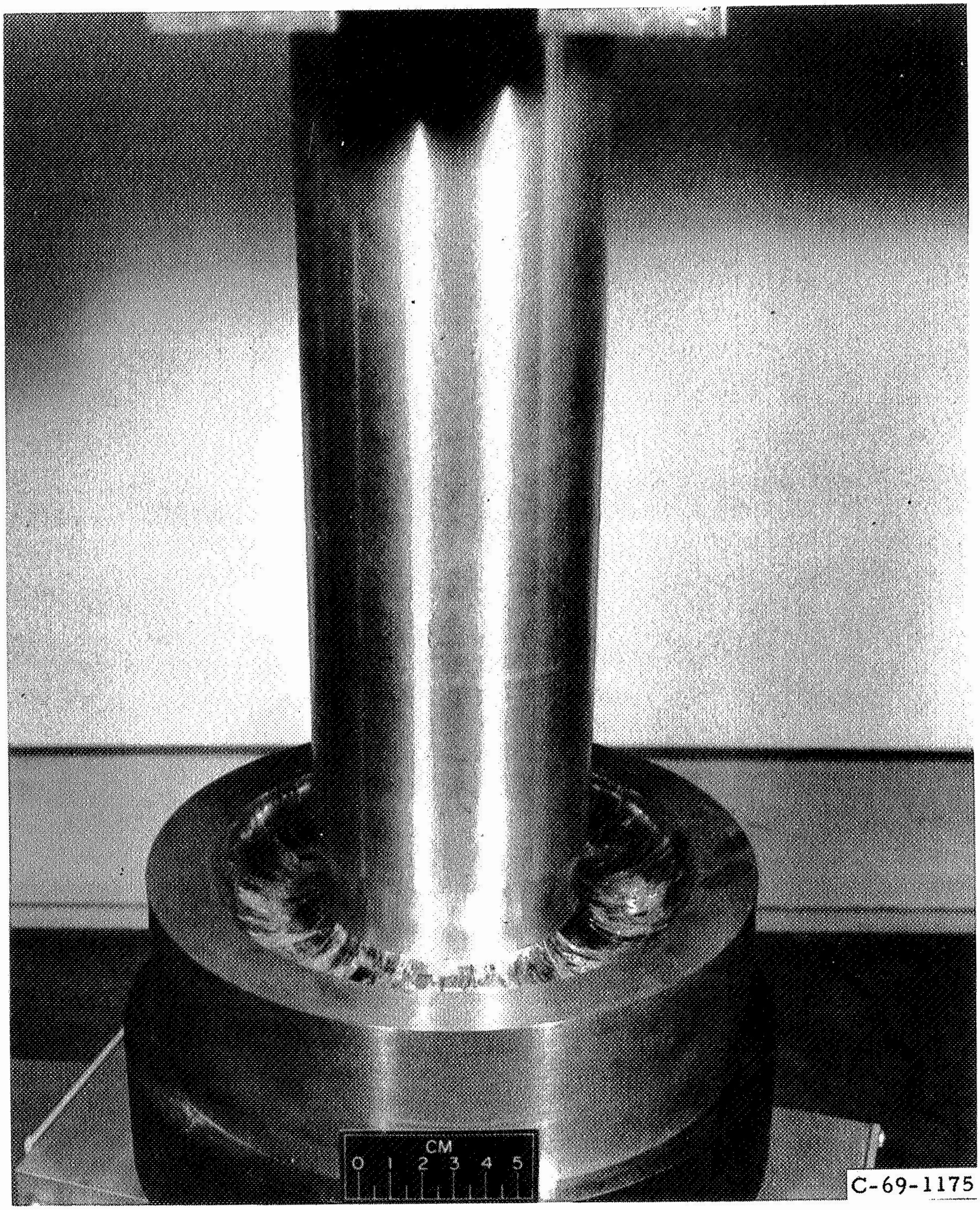


Figure 5. - Frangible tube engages die shank, expansion begins.

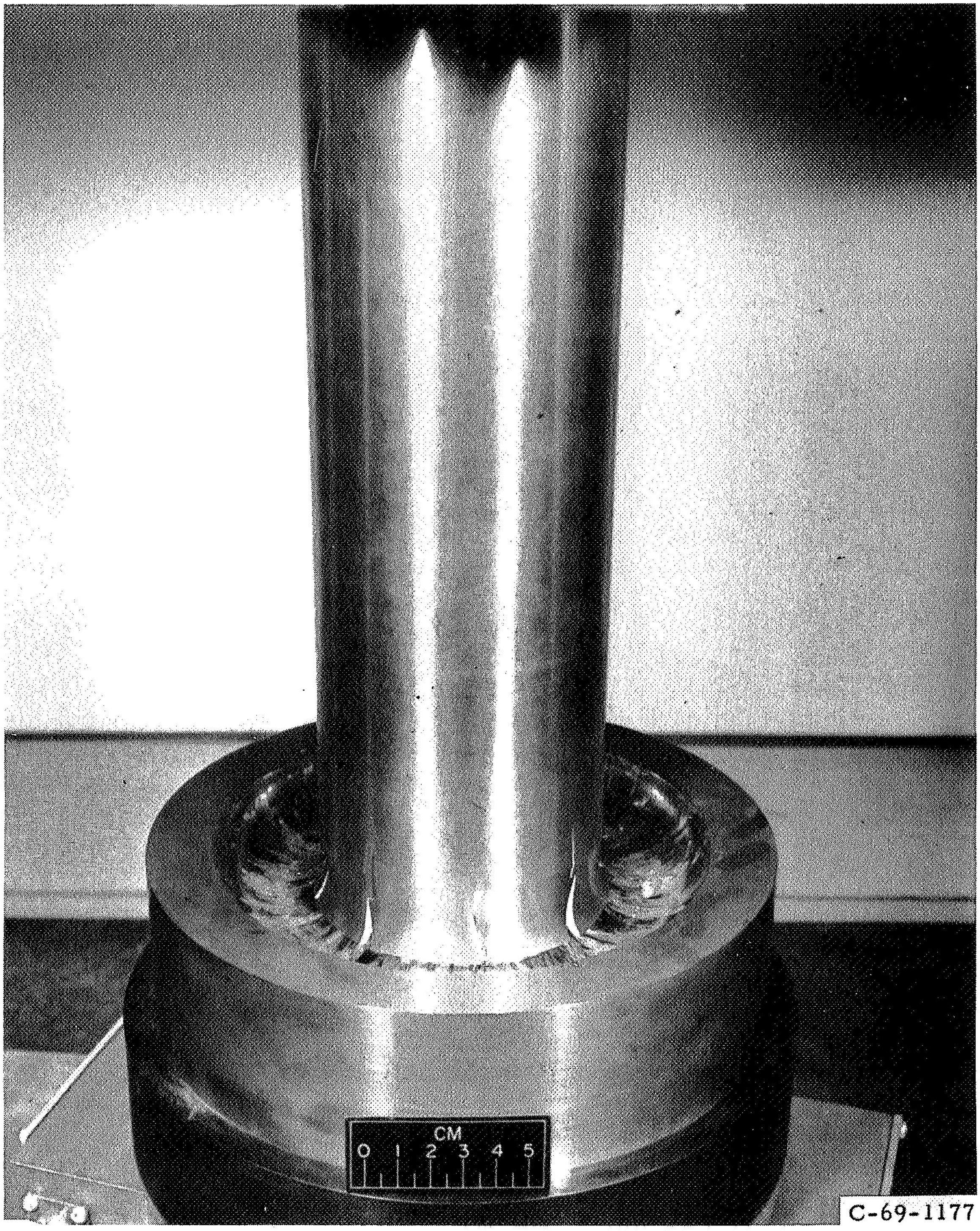
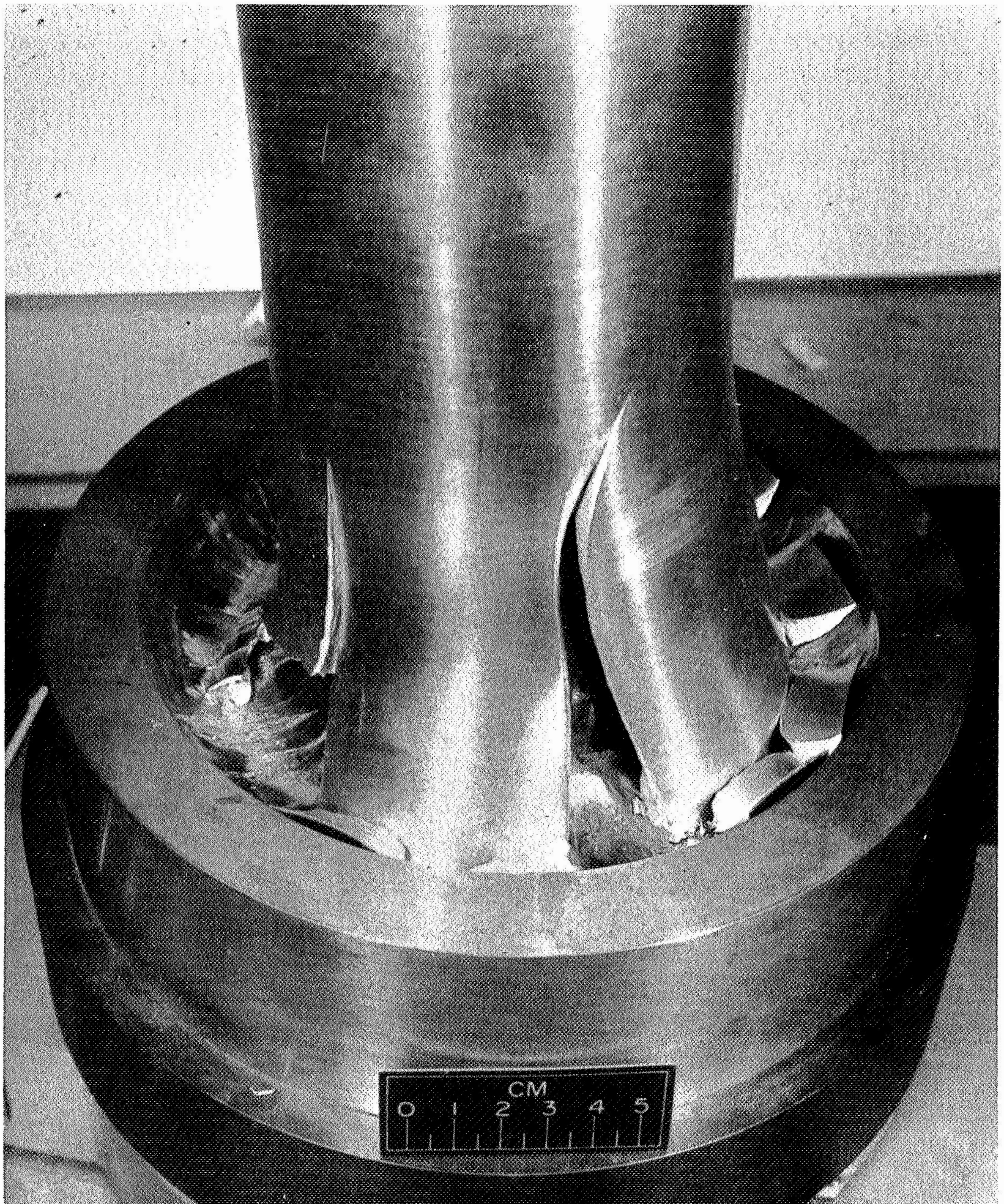


Figure 6. - Longitudinal cracks appear on the frangible tube.

Figure 7. - Longitudinal cracks propagate up the tube.



C-69-1176

Figure 8. - "Tripod effect prevents the tube from franging.

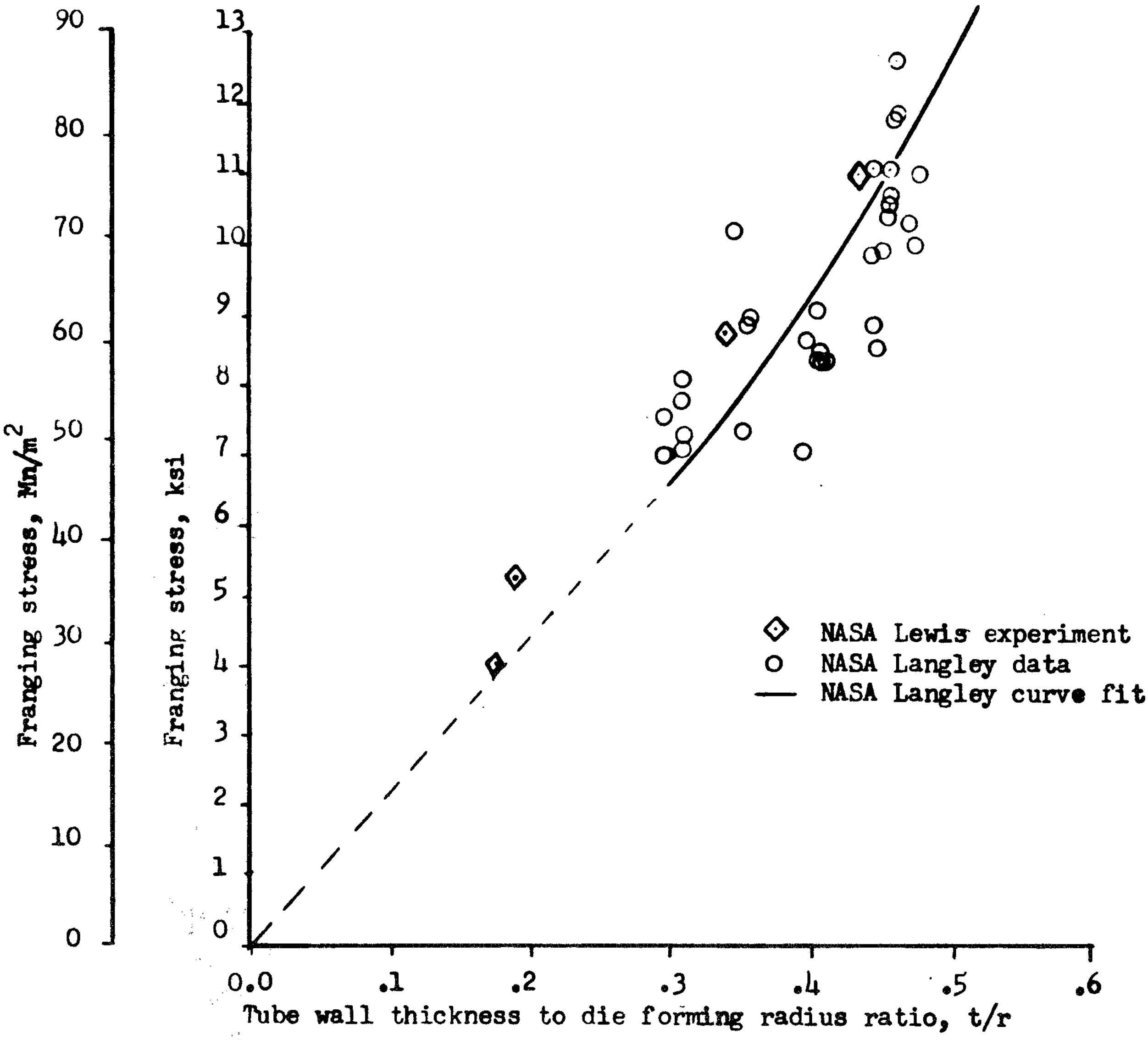


Figure 9. - Franging stress as a function of the tube wall thickness to die forming radius ratio for 2024 T3 aluminum tubes.